The Four-Laser Guide Star Facility (4LGSF) for the ESO VLT Adaptive Optics Facility (AOF)

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Abstract. The 4LGSF is to be installed as a subsystem of the ESO Adaptive Optics Facility (AOF, [1]) on Unit Telescope 4 (UT4) of the VLT, to provide the AO instruments GALACSI/MUSE and GRAAL/HAWK-I with four sodium laser guide stars. The 4LGSF will deploy four modular LGS Units at the UT4 Centrepiece. Two key aspects of the 4LGSF design are: (i) new industrial laser source (fibre lasers) with reduced volume, reduced need of maintenance, higher reliability, simpler operation and optimised spectral format for highly efficient sodium excitation, (ii) modular structure of the four LGS Units, composed of the laser and laser launch telescope, capable to operate independently of the others. The final design of the 4LGSF is now complete and the project has entered the manufacturing, assembly, integration and test phase. Furthermore, modular LGS units containing the laser emitter integrated on the launch telescope have already been demonstrated at ESO in the past years [2, 3]. We believe that having the laser sources as an integral part of a modular unit together with the launching optics offers many advantages at the system level, including the avoidance of laser beam relays, retaining the flexibility to use as many LGS as required independently, and the possibility of building redundancy into the system. Many of these 4LGSF concepts can serve for ELT multi-LGS-assisted adaptive telescope designs and provide a valuable experience in advance of the ELTs.

1. Introduction

The 4LGSF is to be installed as a subsystem of the Adaptive Optics Facility (AOF) on UT4 of the ESO Very Large Telescope (VLT), to provide the AO systems/instruments GALACSI/MUSE and GRAAL/HAWK-I with four sodium laser guide stars (LGSs), as artificial reference sources for the high-order AO corrections.

The 4LGSF will deploy four modular LGS Units (LGSU, see below) at the UT4 Centrepiece, as shown in Figure 1. Each LGS Unit consists of the Launch Telescope System incl. Laser Head and two close-by cabinets, one hosting the Laser Unit electronics (incl. the pump fibre

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laser unit) and the other containing the local control electronics. Two additional 4LGSF cabinets are installed on a new 4LGSF Platform underneath the Nasmyth B platform and contain the computers for independently controlling the four LGS Units. The 4LGSF Platform also hosts the heat exchanger for the laser cooling system.

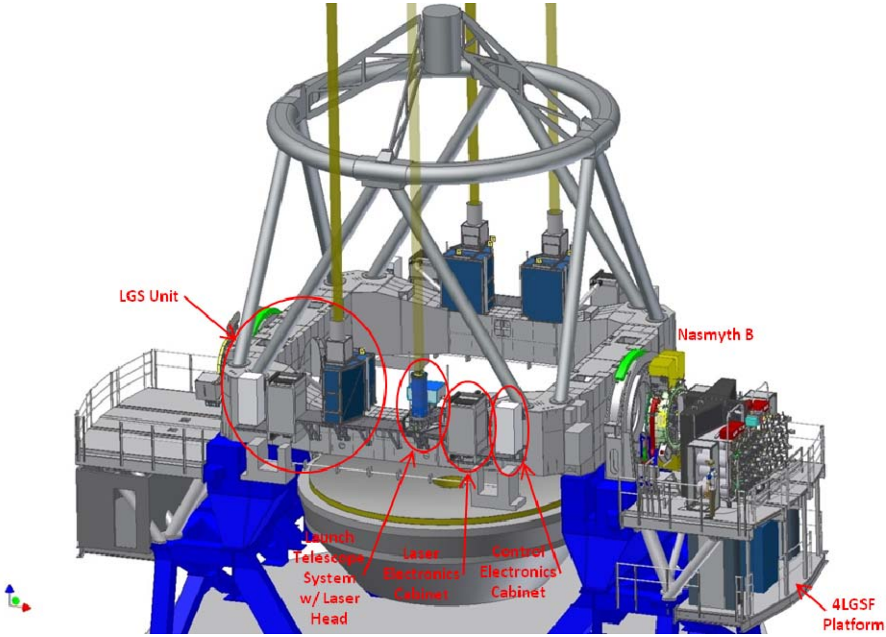

Fig. 1. 4LGSF installation overview. There are two main installation locations: on the Centrepiece and on the 4LGSF Platform underneath the Nasmyth B Platform (to the right). Beside the four Launch Telescope Systems (each including a Laser Head), in total eight cabinets are installed on the Centrepiece for the Laser electronics incl. pump lasers and the local control electronics. Furthermore, connection and distribution boxes are mounted on the Centrepiece for the power and cooling supply. On the 4LGSF Platform two cabinets are installed containing the Local Control Units for the four LGSU and the safety interlock system. The 4LGSF Platform also hosts the heat exchanger of the laser cooling system.

2. Key design aspects

The key aspects of the 4LGSF design are:

- Simplified and improved opto-mechanical design compared to the first-generation LGSF at UT4.
- Modular integrated structure of the four LGS Units, composed of the 22W laser and launch telescope system, each LGSU capable to operate independently of the others.
- New industrial laser source based on fiber Raman amplifiers with reduced need of maintenance, higher reliability and simpler operation.
- Reduced cabling requirements between remote subsystems.

The development of the 4LGSF is based closely on the experience gained with the LGSF that has been developed by ESO in collaboration with external institutes and which is in regular science operation at Paranal Observatory. The two critical long-lead items for the 4LGSF, the Laser System and the Optical Tube Assemblies (OTA) for the laser Launch Telescope Systems (LTS) are procured from industry. The fibre Raman laser technology, on which the 4LGSF Laser System is based, has been developed at ESO and transferred to industry.
Due to the advanced laser technology used in 4LGSF, the preparation time of an observing run with 4LGSF will be considerably reduced compared to the current LGSF.
In addition, by the type of laser technology chosen, the amount of preventative maintenance needed for the 4LGSF will be significantly reduced compared to the existing LGSF which uses a dye laser. We plan to have support contracts from the lasers' provider. The modular approach in the design of the 4LGSF allows that the line-replaceable units (LRUs) (e.g. Laser Head LRU and OTA Field Selector LRU) are interchangeable between the four LGS Units. By this not only the complexity of repairs is significantly reduced (no in-situ re-alignments needed) but also the number of spare parts can be kept low.

3. System Overview

The 4LGSF consists of following six main subsystems:

1. The House Keeping System (HKS). The HKS consists of the common infrastructure of the 4LGSF. The HKS includes the electronics cabinets, Services Connection Points (SCPs) and interfaces with AO and Workstation (WS). The HKS LCU cabinet is installed on the 4LGSF Platform, the additional platform underneath the Nasmyth B platform.
2. Four LGS Units (LGSUs). Each LGSU will be a functional unit able to generate and control a single LGS independently from the other three LGSU.
   Each LGSU is composed of the following components:
   a. A Laser Unit of 22 W continuous-wave output power at 589 nm. The Laser Unit is composed of the Laser Head (installed inside the Launch Telescope System, on top of the Beam Control and Diagnostics System, see below), the Laser Electronics Cabinet (installed on the side of the Centrepiece, close-by to the Launch Telescope System, and also containing the Fibre Pump Laser Unit) and the Laser System Heat Exchanger (installed on the 4LGSF Platform and shared among all Laser Units). The Laser Head and the Laser Electronics Cabinet are both conductively cooled via the Laser System Heat Exchanger. The wavelength of each Laser Unit can be toggled on and off the sodium line for the purpose of background scattering signal calibration.
   b. A Launch Telescope Systems (LTS) mounted on a adjustable Baseplate attached to the Centrepiece and composed of:
      i. A Laser Head, optically pumped via optical fibre by the Pump Laser Unit installed in the associated Laser Unit Electronics cabinet close-by to the LTS. The Laser Head hosts both, the 1178nm Raman Fibre Amplifier Module and the 589-nm frequency-doubling cavity.
      ii. A sealed Beam Control and Diagnostics System (BCDS), fed by the associated Laser Head output. The BCDS comprises the LGS focus correction stage, LGS pointing Jitter Loop Mirror (JLM), safety Output

Shutter (Mirror Shutter) and diagnostics devices. The JLM is used to control the uplink laser beam in order to stabilise the downlink position of the corresponding LGS on the associated AO wave-front sensor. With the help of the Mirror Shutter the laser beam propagation into air is turned on/off. The diagnostics devices comprise a Laser Bolometer (BOL) for offline power measurements during operation; it is fed via the Mirror Shutter. The remainder of the diagnostics devices is used for off-line maintenance purposes.

iii. A sealed Optical Tube Assembly (OTA) of 30 cm clear aperture, fed by the collimated output beam from the BCDS, for the final projection of a circularly polarised laser beam onto sky. The OTA comprises the Field Selector which is used for preset pointing of the LGS and offloading the JLM. Temperature and air pressure sensors are used to maintain the LTS performance under environmental changes during operation.

iv. A Cover by which the Laser Head, BCDS and OTA are protected from wind. When 4LGSF is not in use, the OTA exit optics is protected by a remotely controlled Cover Shutter.

v. A short Baffle, extending from the OTA exit, to minimise the thermal radiation cooling of the OTA exit optics.

c. A Control Electronics Station, composed of the electronics devices and infrastructure used to monitor and control the associated LGSU.

d. A Safety Interlock System Sub-Station which will interface the LGSU and associated Control Electronics Station with the Safety Interlock System CPU; Both, the Control Electronics Station and the Safety Interlock System Sub-Station are physically located in a single conductively and water-cooled cabinet bolted to the UT4 Centrepiece close to the LTS

e. A Local Control Unit (LCU), which will run the high-level control SW to operate the associated LGSU. The LCU will control the LTS and associated Laser Unit through the Control Electronics Station. The LCU of each LGSU is installed in one of the two electronic cabinets on the 4LGSF Platform underneath the Nasmyth B platform.

3. The Safety Interlock System (SIS), including the already existing Aircraft Avoidance System (AAS) with its two aircraft detection cameras mounted on the UT4 Top Ring. The 4LGSF SIS additionally interfaces with the LGSF in order to provide the AAS signals to it. The SIS CPU is installed in the HKS cabinet on the 4LGSF Platform underneath the Nasmyth B platform.

The 4LGSF control system is based on the VLT Instrument Control Software and is thought as a sub-system of the AOF, having its own Observation Software. Several control loops are implemented for the operation of the 4LGSF:

- A focus (open) loop for each LGSU in order to keep the uplink beam focused on the mesospheric sodium layer as a function of LTS temperature, LTS air pressure and UT4 pointing altitude;
- A LGS fast pointing jitter loop for each LGSU using the JLM as actuator, incl. offloading to the LTS Field Selector, with the control signals provided by AO;

- A LGS position tracking (open) loop for each LTS Field Selector, for maintaining the LGS on its preset on-sky position, compensating for field rotation, used during maintenance with the UT4 guider camera, as a function of UT4 pointing angle and temperature;
- The output frequency stabilisation loop of the Laser System, which is part of the self-contained control system in each Laser Unit.

4. Laser System design

In order to minimise the optical losses between the high-power laser sources and the LTSs, the 4LGSF Laser Units are located in the direct proximity of the individual LTSs, by this avoiding a cumbersome laser beam delivery system.

This requires compact and ruggedized lasers as both the space as well as in-situ maintenance activities at the UT4 Centrepiece are limited. We are convinced that having the laser sources as an integral part of a modular unit together with the launching system is the best approach to follow at system level, which allows skipping complicated and lossy beam relays, and retains the flexibility of using independently the four laser guide stars.

The 4LGSF laser system comprises four Laser Units and one Heat Exchanger. Each of the autonomous Laser Units is based on a master oscillator power amplifier (MOPA) design with subsequent second harmonic generation (SHG), delivering each a total optical power of 22 W at 589 nm. 2 W of the emitted laser power is used for optical back-pumping of the mesospheric sodium atoms in order to enhance the brightness of the LGS (see also [4]).

The master oscillator comprises a single-frequency diode laser actively stabilized to twice the wavelength of the sodium transition via a high-precision wavelength meter. The output of the diode laser serves as a seed signal for a single Raman fibre amplifier (RFA). The amplified optical signal is frequency-doubled in an external enhancement resonator [5].

Each laser system is individually controlled by a microcontroller based on a PowerPC running Linux. All communication with the 4LGSF is carried out via an external interface board directly connected to the microcontroller. There is no communication between the individual laser units.

The Laser Unit is subdivided into functional modules: the Seed Laser Module, the Amplification Module and the Frequency Doubling Module. Spatially, each Laser Unit is divided into the Laser Head and the Electronics Cabinet. The seed laser module is located in the electronics cabinet; the amplification module is subdivided into the fibre pump laser located in the electronics cabinet and the Raman amplifier located in the laser head. The frequency doubling module is located in the laser head.

Physically, the laser head is installed on top of the LTS BCDS and the laser electronics cabinet is installed in close proximity on the side of the centrepiece (see Figure 2). The two parts are connected via two flexible hoses, one of them enclosing the cooling tubes, the other one electrical and fibre-optical cables.

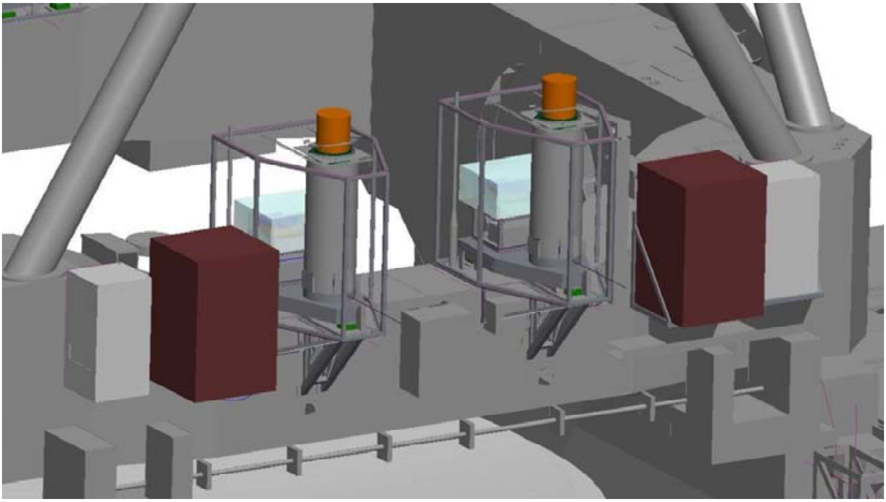

Fig. 2. Arrangement of the laser system installed on the centrepiece. Two Laser Units are shown of which each Laser Head (coloured light blue) is installed directly on top of the BCDS structure of a LTS. The laser electronic cabinet (in brown colour) is installed near-by, on the side of the centrepiece. Not shown here is the heat exchanger on the 4LGSF Platform as part of the isolated laser cooling system. The light-grey coloured cabinets contain the local control electronics for the LTS. The LTS cover panels and light baffles have been removed for clarity.

A liquid-liquid heat exchanger is used to provide the laser units with cooling water of well-defined temperature of 15°C ± 1 K and is located in a cabinet on the 4LGSF Platform.

5. LTS optical design

The LTS optics is modular, with two cascaded beam expanders, the first one as part of the BCDS and the other being the OTA itself (see Figures 3 and 4). This approach eases the overall alignment and simplifies the integration.

The BCDS preceding the OTA in the optical train contains, besides laser beam diagnostic devices:

1. A pair of mirrors (dichroic D1, and M2) folding the input laser beam
2. A 3.6x afocal Beam Expander Unit (BEU) with motorized focusing capability. The BEU receives at its optical input interface a 4.2 mm diameter beam from the laser (3.0mm waist diameter), and produces a 15.0mm diameter beam output
3. A solenoid actuated safety shutter (Mirror Shutter) to propagate the laser beam on-sky. It sends the laser beam to a cooled bolometer acting as absolute power meter when there is no laser propagation to the mesosphere
4. A piezoelectric steering mirror (JLM), 25mm in diameter, to correct the uplink beam jitter induced by the turbulence in the atmosphere. This mirror is the actuator of a jitter control loop. The mirror steers the 15.0mm laser beam, will be used within a range of ±3 arcsec on sky and has a temporal bandwidth of 1 kHz.

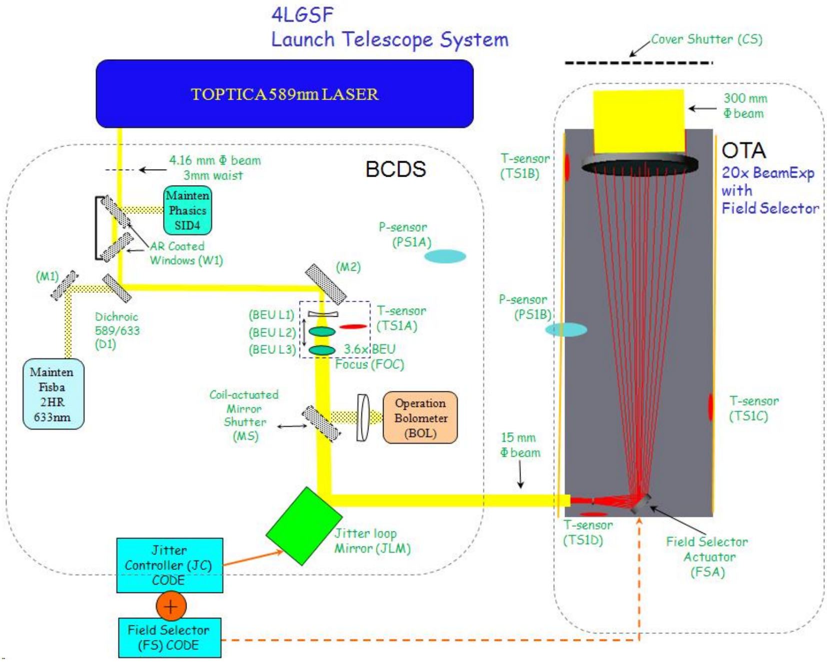

Fig. 3. Schematic layout of the LTS with BCDS (left) and OTA (right). Note also in parenthesis the acronyms assigned to the different LTS components. Note that in this layout the quarter-wave plate element at the OTA entrance to produce the output circular polarization is not shown.

Note that the only laser beam diagnostics device used in normal operation is the bolometer. The Maintenance PHASICS and FISBA interferometers indicated in Figure 3 are only used in case of corrective/on-demand maintenance.

Also note that the BCDS housing and support structure hold the Laser Head and that the laser output waist location is at the input optical interface of the BCDS (as indicated in Figure 3).

The OTA is an afocal 20x beam expander [6], which produces a 300mm diameter beam at the output, receiving the input laser beam of 15mm in diameter from the BEU in BCDS.

The OTA consists of four optical elements: a quarterwave plate to produce circular polarisation, a small negative lens, a 75mm diameter folding flat mirror, and a large positive lens at the output. The large lens of OTA has one aspherical surface and works at f/4.52, allowing relaxed tolerances. The field selector function is done by the OTA, with a slow-moving (1Hz refresh rate foreseen) motorised steering mirror 75mm in diameter, inserted in the diverging beam produced by the OTA negative lens L1.

Note that besides the BEU in the BCDS also the OTA is equipped with temperature sensors located next to the lenses and on the support structure, as well as an absolute air pressure sensor.

The LTS assembly will be mounted on the centrepiece of UT4 on three points using levelling devices to allow accurate and reproducible alignment of the LTS Baseplate (Figure 4).

Fig. 4. LTS without Cover and Baffle. The OTA is to the right. On top of the BCDS (to the left) the Laser Head is installed. The Laser Head output beam is entering the BCDS vertically from the top. The LTS Baseplate hosting the Laser Head, BCDS and OTA is installed on the UT4 Centrepiece using three tilt adjusters and can be removed and re-installed without re-alignment.

6. Conclusion

The challenge in the 4LGSF design is to fulfil the stringent performance requirements, for both, operation and maintenance. The final design of the 4LGSF shows that this is actually possible within the given boundary restrictions.

Although the 4LGSF is retro-fitted to a telescope already in operation, we believe that the 4LGSF modular LGSU concept presented in this document can serve as a future reference for multi-LGS-assisted adaptive telescope designs developed for ESO. In particular for the planned E-ELT project, the 4LGSF represents an invaluable path-finder and experience, as the E-ELT design shall use from the start multiple sodium LGS.

7. References

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